

Stephan P. GALOS^{1*}, Christoph KLUG¹, Roberto DINALE²

The 2023 glacier inventory for South Tyrol in the context of the 1997, 2005, and 2017 inventories

Short Communication

Abstract: Galos S.P., Klug C., Dinale R., *The 2023 glacier inventory for South Tyrol in the context of the 1997, 2005, and 2017 inventories*. (IT ISSN 0391-9838, 2024). This paper presents a new glacier inventory for the region of South Tyrol, Italy. Referring to the glacier state of the year 2023, it is the fourth contribution to the series of homogenized glacier inventories for this region following the inventories of 1997, 2005, and 2017, which were also revised in the course of this study. The 2023 inventory includes 729 glacier parts across seven mountain groups covering a total area of 72.1 km². Comparison with the previous inventories reveals an area loss of 13.8 km² (-16.1%) between 2017 and 2023, and 50.1 km² (-41.0%) between 1997 and 2023. Although significant glacier retreat is observed throughout the study area, relative area loss is lower in mountain groups west of the Eisack/Isarco River (except for the Texel Group) than in the eastern ranges, likely due to topographic controls. In all mountain groups, the 2017-2023 loss rate exceeds that of the 2005-2017 period. The average surface elevation change of glacierized areas since the 2017 inventory is -8.7 ± 0.14 m, corresponding to a total volume loss of approximately 0.75 ± 0.03 km³ and a mass loss of 635 ± 61 million tons across the study region.

Key words: Climate change, Alpine glacier decay, Glacier inventory, Aerial imagery.

Riassunto: Galos S.P., Klug C., Dinale R., *Il catasto dei ghiacciai dell'Alto Adige del 2023 nel contesto dei catasti del 1997, 2005 e 2017*. (IT ISSN 0391-9838, 2024). Il presente articolo descrive un nuovo catasto dei ghiacciai dell'Alto Adige (Italia) relativo all'anno 2023, che rappresenta il quarto contributo alla serie dei catasti dei ghiacciai omogeneizzati di questa regione dopo quelli del 1997, 2005 e 2017, che, nell'ambito dello stesso lavoro, sono stati a loro volta rivisti. Il catasto del 2023 comprende 729 ghiacciai, suddivisi in sette gruppi montuosi, che coprono una superficie totale di 72,1 km². Il confronto con i catasti precedenti mostra una perdita di superficie di 13,8 km² (-16,1%) nel periodo 2017-2023 e di 50,1 km² (-41,0%) nel periodo 1997-2023. Sebbene l'intera area di studio sia interessata da un significativo regresso dei ghiacciai, nei gruppi montuosi a ovest del Fiume Isarco, con la sola eccezione del Gruppo di Tessa, la perdita relativa di superficie risulta inferiore rispetto a quella registrata nei settori orientali della provincia, verosimilmente in virtù di un diverso condizionamento topografico. In tutti i gruppi montuosi, il tasso di perdita nel periodo 2017-2023 risulta superiore rispetto al periodo 2005-2017. La variazione media dell'elevazione della superficie delle aree glacializzate rispetto al catasto del 2017 è pari a $-8,7 \pm 0,14$ m, corrispondenti a una perdita di volume di circa $0,75 \pm 0,03$ km³ e a una perdita di massa di 635 ± 61 milioni di tonnellate nell'intera area di studio.

Termini chiave: Cambiamento climatico, Regresso dei ghiacciai alpini, Catasto dei ghiacciai, Immagini aeree.

INTRODUCTION

In recent years, the retreat of mountain glaciers has accelerated globally (e.g., Hugonnet *et al.*, 2021; Dussaillant *et al.*, 2025). In this context, regularly updated glacier inventories form the basis for studies on the effects of climate change on the cryosphere (e.g., Hartl *et al.*, 2025; Schuster *et al.*, 2025) and related environmental impacts, such as runoff contribution (e.g., Galos *et al.*, 2015; Wimberly *et al.*, 2025) or sea level rise (e.g., Marzeion *et al.*, 2020; Dussaillant *et al.*, 2025).

For the region of South Tyrol, the investigation area of this study, the last regional survey was performed in 2016/2017 resulting in the 2017 glacier inventory for South Tyrol (Galos *et al.*, 2022; Galos *et al.*, 2023). Since then, the glaciers of the study region, as in the entire European Alps, have again been affected by a massive decline (WGMS, 2025). Especially the summers of 2017, 2018, 2022, and 2023 resulted in significant losses in area and volume for the glaciers of the region, with 2022 standing out in particular: Exceptionally low winter snow reserves, combined with a prolonged and intense ablation period without significant summer snowfall, resulted in the surpassing of previous record annual mass losses in many cases (e.g., Baroni *et al.*, 2023; Voordendag *et al.*, 2023; Berthier *et al.*, 2024; GLAMOS, 2024).

¹ Universität Innsbruck, Innrain 52, 6020 Innsbruck, Austria.

² Office for Hydrology and Dams - Civil Protection Agency, Drususallee 116, 39100 Bolzano Italy.

* Corresponding author: Stephan P. Galos (Stephan.Galos@uibk.ac.at)

Against this background, the aim of the present study is to expand the existing dataset of the homogenized South Tyrolean glacier inventories and thus to provide a new inventory of the remaining glaciers in the study area. Based on new data of a survey in 2023, the three existing glacier inventories for 1997, 2005 and 2017 were also updated. In particular, the 2017 inventory was revised based on the differential digital terrain model (dDTM) now available for 2017-2023. Consequently, the results and analyses presented here refer to the new or updated 2025 versions of the inventories, as published on ZENODO (Galos *et al.*, 2025) and the GeoBrowser MapView of the Province of Bolzano (Autonomous Province of Bolzano South Tyrol, 2025. GeoBrowser MapView, <https://mapview.civis.bz.it/>, last access: 28 August 2025). A detailed compilation of references to previous and historical inventories for the study area can be found in Galos *et al.* (2022).

STUDY AREA

The study area encompasses the high mountain regions of South Tyrol and, for glaciers extending beyond provincial borders, includes small adjoining parts of Austria and the neighboring Italian regions of Trentino, Lombardy, and Veneto. The surveyed glaciers are assigned to seven main mountain groups: Ortler Alps, Ötztal Alps, Texel Group, Stubai Alps, Zillertal Alps, Hohe Tauern, and Rieserferner Group (fig. 1). The Sesvenna Group, represented by a single glacier in the 1997 inventory, is not included, as this glacier has since disappeared.

Most of the glaciers in the study area are situated along or south of the main ridge of the Eastern Alps. Due to the topographic shadowing effect that prevents precipitation from the north, the region is predominantly influenced by southerly airflows. While the valleys receive relatively low annual precipitation (approximately 500-800 mm), values increase to around 1500 mm at 3000 m a.s.l. (Strasser *et al.*, 2018). The mean annual air temperature at this elevation is approximately -3 °C.

DATA AND METHODS

Orthophotos and Digital Terrain Model (DTM)

The new 2023 inventory is based on stereo orthophotos acquired during an aerial survey conducted between 7 and 9 September 2023. The campaign was commissioned by the Office for Hydrology and Dams of the Civil Protection Agency of the Autonomous Province of Bolzano-South Tyrol and carried out by AVT-Vermessung ZT-GmbH (Imst, Tyrol, Austria). At the time of acquisition, weather conditions were almost entirely cloud-free, and only a few areas along the margins of some glaciers were covered with

snow from the previous winter. There was hardly any fresh snow on the glaciers except for some minor remnants in the Ortler Alps associated with a cold front at the end of August. The result is a high-quality dataset of high-resolution orthophotos and derived DTMs for the glaciers of South Tyrol without significant spatial data gaps.

The raw data was processed by AVT-Vermessung ZT-GmbH, using the same georeferencing framework as for the 2017 inventory (Galos *et al.*, 2022). Detailed checks confirmed that additional horizontal co-registration was unnecessary. The orthophotos have a horizontal ground resolution of approximately 0.1 m, while the derived DTMs have a resolution of 0.5 m. The mean vertical square deviation from the 2017 DTM over selected stable areas is about 0.2 m, with a mean bias of -0.14 m relative to the 2017 data. This offset likely reflects technical differences in data acquisition but could not be fully explained. Given the research objectives and accuracy requirements, no bias correction was applied as the magnitude of this bias is negligible for the inventory methodology. For hydrological interpretations, such as mass change estimates, uncertainties are mainly controlled by uncertainties in ice-density. Considering the pronounced surface-elevation changes during the study period, the influence of ice-density uncertainty exceeds that of the DTM bias by nearly an order of magnitude.

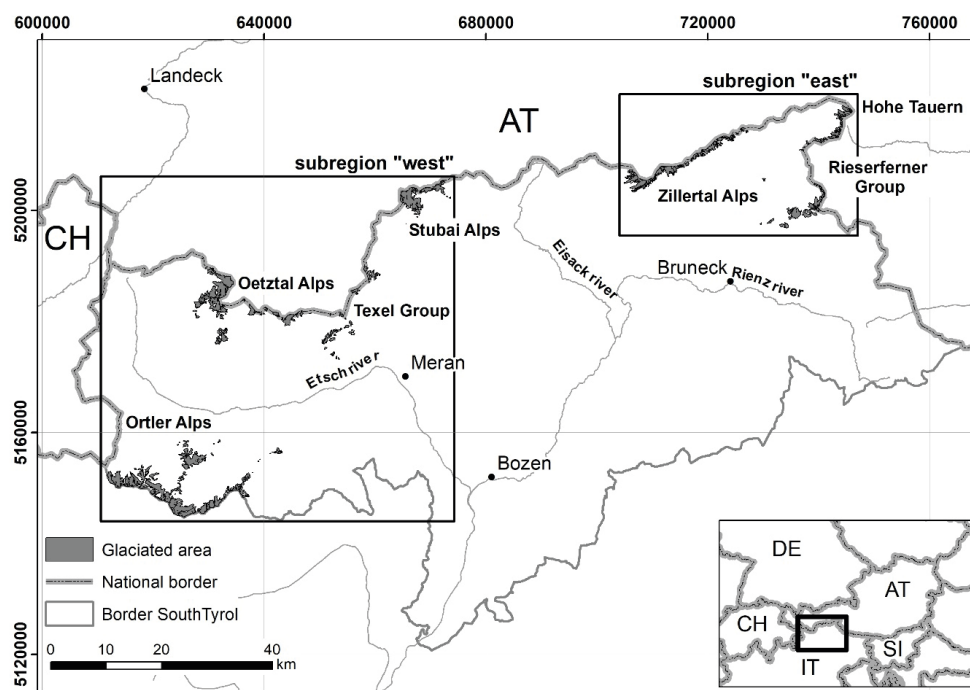
Delineation of glacierized areas

The delineation of glacier areas for the 2023 inventory followed the established methodology of Abermann *et al.* (2009), which was also applied in the 1997, 2005, and 2017 inventories. Glacierized areas were identified either directly, where bare ice was visible, or indirectly, in debris-covered zones, based on surface curvature, crevasse patterns, edge fractures, or similar structures. Remnants of glacier parts included in earlier inventories were recorded, if possible, if their area exceeded 0.0001 km² (=100 m²). While 0.01 km² typically represents the lower area threshold for glaciers in large-scale inventories (e.g., Pfeffer *et al.*, 2014), a smaller threshold was intentionally applied here due to the manageable extent of the study area, the high spatial resolution of the available data, and the potential relevance of the results for process-oriented analyses.

Revision of the 1997, 2005, and 2017 inventories

As part of this study, the glacier inventories of 1997, 2005, and 2017 were revised. The availability of the dDTM for the period 2017-2023 enabled several adjustments, particularly for the 2017 inventory, where glacier areas had in some cases been underestimated because some heavily debris-covered sections were originally classified as ice-free. In addition, several previously unrecognized glacier parts

Figure 1 - Map of the study region (adapted from Galos *et al.*, 2022), showing the main mountain groups and the locations of the glaciers investigated. The grid indicates UTM coordinates.



were incorporated. These revisions resulted in a total glacier area approximately 1.9 km² (2.3%) larger than in the original 2017 inventory.

Revisions to the 2005 and 1997 inventories were considerably less extensive and mainly addressed inconsistencies between inventories regarding the glaciers included, as well as minor corrections to glacier outlines based on new evidence. For example, marginal zones previously unclassified as glacierized could now be identified as such due to pronounced vertical surface changes. Overall, the updates resulted in an increase of 0.30 km² (+0.3%) for the 2005 inventory and 0.27 km² (+0.2%) for the 1997 inventory, remaining well within the expected range of methodological uncertainty.

Note that the 1997 inventory is based on orthophotos acquired during the 1992-1997 period, whereas the 2017 inventory was derived from 2016 orthophoto data in the western part of the study area and 2017 data in the east (Galos *et al.*, 2022). For simplicity, periods between inventories are referred to by the nominal year of the respective inventory throughout the manuscript (e.g., 1997-2023 or 2017-2023).

RESULTS AND DISCUSSION

The 2023 Glacier Inventory

The new 2023 glacier inventory for South Tyrol reveals a glacierized area of 72.1 km², spread over a total of 729 individual glacier parts. With 30.1 km², the Ortler Alps account for around 42% of the total glacier area followed

by the Ötztal Alps with 17.9 km² (25%). Relatively large glacierized areas can still be found in the Stubai Alps with 8.2 km² (11%) and the Zillertal Alps with 6.8 km² (9%). The Rieserferner Group with 4.8 km² (6%), the Hohe Tauern with 2.9 km² (4%) and the Texel Group with 1.7 km² (2%) make up only a relatively small proportion of the total glacierized area in the study area (table 1). Although the smallest size class (<0.1 km²) with 625 individuals accounts for around 86% of the recorded glacier parts, this class only covers an area of 7.3 km² or 10% of the total area. By far the largest share of the total glacierized area is accounted for by the size class of 1-5 km², which comprises 17 glacier parts and a total area of 33.4 km². The only remaining glacier part with an area larger than 5 km² is the main part of the Übeltalferner (Ghiacciaio di Malvalle) in the Stubai Alps, which now covers about 5.3 km².

Changes in glacier area

Since the 1997 inventory, total glacier area has decreased from 122.2 km² to 104.1 km² in 2005, to 85.9 km² in 2017, and finally to 72.1 km² in 2023 (table 2). Especially since the 2005 inventory, relative area loss has been greater in the eastern part of the study region than in the west, except for the Texel Group, which contains small and highly responsive glaciers and exhibits by far the largest relative changes in the western part of the region. For the period between the 1997 and 2005 inventories, this pattern was less pronounced, as the Hohe Tauern glaciers showed a similar relative decline (-12.9%) to those in the

Table 1 - The new 2023 glacier inventory in numbers. S_{ref} denotes total glacier area, N the number of glacier parts, and S_{ref}/N the mean area per glacier part. Units for size classes are km^2 .

					Glacier parts per size class					Total area per size class				
		S_{ref}	N	S_{ref}/N	<0.1	0.1-0.5	0.5-1	1-5	>5	<0.1	0.1-0.5	0.5-1	1-5	>5
	Mountain group	[km^2]		[km^2]	[km^2]	[km^2]	[km^2]	[km^2]	[km^2]	[km^2]	[km^2]	[km^2]	[km^2]	[km^2]
West	Ortler Alps	30.1	212	0.14	179	17	6	10		2.1	4.0	4.2	19.9	
	Ötztal Alps	17.9	139	0.13	114	17	3	5		1.6	3.8	1.9	10.7	
	Stubai Alps	8.2	55	0.15	48	4	2		1	0.5	1.0	1.4		5.3
	Texel Group	1.7	41	0.04	35	6				0.5	1.3			
East	Hohe Tauern	2.9	51	0.06	43	7	1			0.6	1.5	0.8		
	Rieserferner G.	4.4	61	0.07	50	10		1		0.5	2.4		1.5	
	Zillertal Alps	6.8	170	0.04	156	11	2	1		1.4	2.3	1.8	1.3	
	South Tyrol	72.1	729	0.1	625	72	14	17	1	7.2	16.2	10.0	33.4	5.3

Table 2 - Total glacier area, absolute and relative area changes, and corresponding annual rates for individual mountain groups and for the entire study area across the four homogenized glacier inventories.

Glacier area [km ²]						Area change [km ²]			Area change [%]			Annual rate [% a ⁻¹]		
	Mountain group	1997	2005	2017	2023	97-05	05-17	17-23	97-05	05-17	17-23	97-05	05-17	17-23
West	Ortler Alps	47.4	40.8	35.2	30.1	-6.6	-5.6	-5.0	-14.0	-13.7	-14.3	-1.9	-1.3	-2.2
	Ötztal Alps	29.1	25.4	21.3	17.9	-3.8	-4.0	-3.4	-12.9	-15.9	-16.1	-1.7	-1.6	-2.5
	Stubai Alps	12.5	10.8	9.4	8.2	-1.6	-1.4	-1.2	-13.0	-13.0	-13.0	-1.7	-1.3	-2.0
	Texel Group	3.5	2.6	2.2	1.7	-0.8	-0.5	-0.4	-24.0	-17.8	-20.1	-3.4	-1.8	-3.1
East	Hohe Tauern	5.6	4.8	3.5	2.9	-0.7	-1.3	-0.6	-12.9	-26.8	-18.3	-1.7	-2.6	-3.3
	Rieserferner G.	9.0	7.4	5.4	4.4	-1.6	-2.0	-1.0	-17.3	-27.4	-19.0	-2.3	-2.6	-3.5
	Zillertal Alps	15.1	12.2	8.9	6.8	-2.8	-3.4	-2.0	-18.8	-27.7	-22.8	-2.6	-2.7	-4.2
	South Tyrol	122.2	104.1	85.9	72.1	-18.0	-18.2	-13.8	-14.8	-17.5	-16.1	-2.0	-1.7	-2.6

Ortler Group, Ötztal Alps, and Stubai Alps. However, glacier decline in the Zillertal Alps and the Rieserferner Group was significantly greater even during this period, which was marked by the unprecedented melt of summer 2003. Differences among mountain groups are primarily controlled by glacier size, topography, and geomorphological setting rather than local climatic variability. Larger glaciers generally show smaller relative area losses, and vice versa (e.g., Abermann *et al.*, 2011). This explains, for instance, the contrast between the small glaciers of the Texel Group and the Stubai Alps, which are dominated by the large Übeltalferner. The pronounced retreat in the Zillertal Alps and other eastern ranges partly reflects the prevalence of thin but extensive cirque glaciers, where ice-thickness loss translates into substantial areal reduction. Many glaciers have already fragmented into smaller parts, further accelerating melt through feedbacks such as the loss of the self-cooling effect of larger glaciers (Carturan *et al.*, 2015) and increased longwave radiation from adjacent ice-free terrain.

The mean annual area change rate of $-1.7\% \text{ a}^{-1}$ for 2005-2017 exceeds the $-1.3\% \text{ a}^{-1}$ reported by Paul *et al.* (2020)

for the entire Alps (2003-2015/16) but closely matches the $-1.8\% \text{ a}^{-1}$ derived from the results of Hartl *et al.* (2025) for the Austrian Ötztal and Stubai Alps (2006-2017/18). For 2017-2023, the rate increased to $-2.6\% \text{ a}^{-1}$, indicating accelerated glacier retreat under the exceptionally warm conditions during this period.

Glacier area decreased significantly across all elevation bands (fig. 2). Compared to 2017, the largest absolute loss (-2.2 km^2) occurred between 2900 and 3000 m a.s.l., while the strongest relative decline (-31%) was observed between 2500 and 2600 m a.s.l. Over the full 1997-2023 period, absolute loss peaked at -8.1 km^2 in the 2900-3000 m band, and relative retreat reached -62% between 2400 and 2500 m a.s.l. The elevation of maximum glacier area shifted from 3000-3100 m a.s.l. in 1997 to 3100-3200 m a.s.l. in the subsequent inventories. The median elevation of the glaciers recorded rose from 3013 m a.s.l. in 1997 to 3046 m a.s.l. in 2017 and 3050 m a.s.l. in 2023.

Compared to the 2017 inventory, 122 of the 571 glacier parts documented are no longer present in 2023. All extinct glacier parts belonged to the smallest size class of $<0.1 \text{ km}^2$ in 2017. Relative to the 1997 inventory, 70

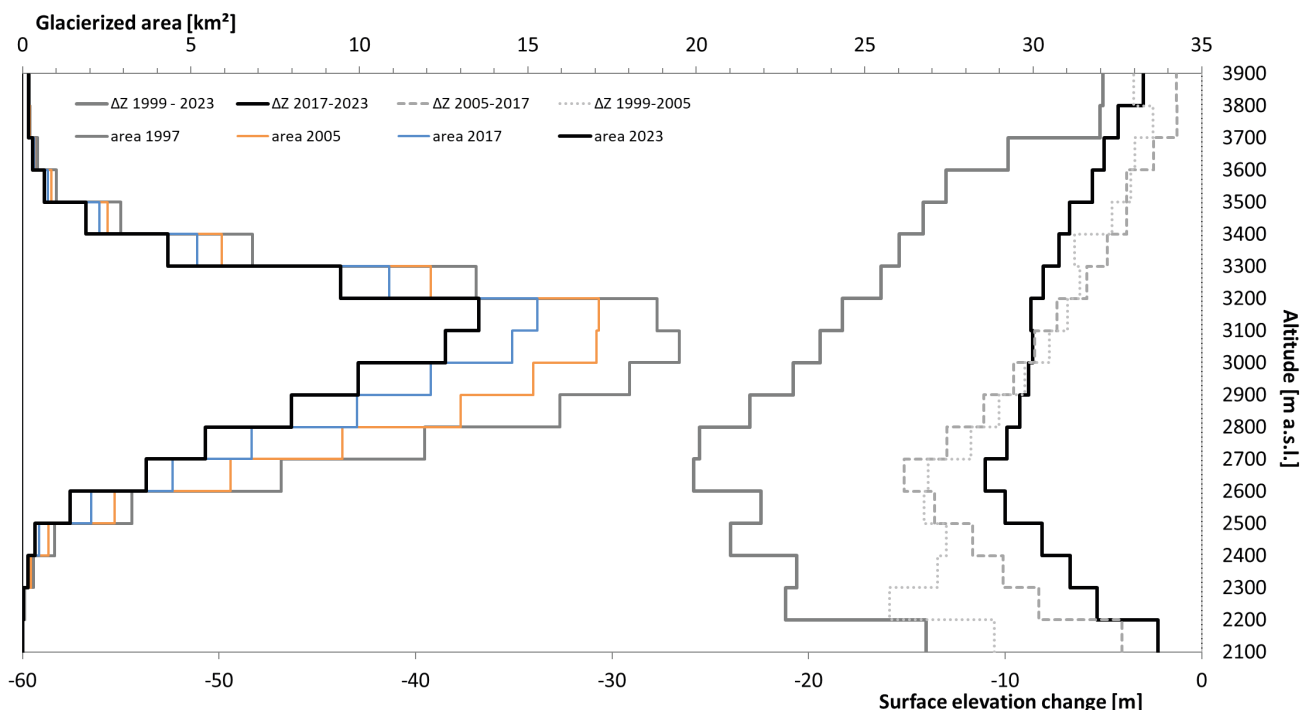


Figure 2 - Average surface-elevation change by elevation band for the periods between inventories, along with the elevation distribution of glacier area to aid interpretation. The 2017-2023 period is characterized by a markedly reduced altitudinal gradient in observed glacier surface elevation change.

glacier parts have disappeared by 2023, including two glacier parts exceeding 0.1 km² in 1997. The largest absolute changes in both periods occur within the 1-5 km² size class, which also accounts for the largest share of total glacier area (table 3).

While for all other size classes, both the number of glacier parts and their cumulative areas show a continuous decline, the number of glacier parts in the smallest size class (<0.1 km²) has increased markedly: from 172 glacier parts in 1997 to 451 in 2017 and 625 in 2023 (table 4). When applying an area threshold of 0.01 km² instead of 0.0001 km², the number of glacier parts in the smallest size class changes to 134 (totaling 5.8 km²) in 1997, 143 (5.3 km²) in 2005, 172 (5.9 km²) in 2017, and 161 (6.1 km²) in 2023. This indicates that most of the increase occurs at the lower end of the size spectrum. Although the minimum area threshold of 0.0001 km² in our study was consistently applied across all inventories, part of the observed rise, particularly among the smallest glacier parts, can be attributed to the progressively improved quality of orthophotos and DTMs (especially after 1997), which enhanced the detection of very small glacier fragments. Nevertheless, even between the 2017 and 2023 inventories, both based on high-resolution datasets of comparable quality, the number of glacier parts in the smallest size class rose from 451 to 625, indicating that the increase in glacier fragmentation in the study area is most pronounced below 0.01 km².

Changes in surface elevation, volume and mass

The mean surface-elevation change across the study area since the 2017 inventory is -8.7 ± 0.14 m, corresponding to an average annual rate of -1.27 ± 0.06 m a⁻¹. This value lies between the rate of -0.92 m a⁻¹ reported by Hartl *et al.* (2025) for the Austrian Ötztal and Stubai Alps (2006-2017/18) and the -1.52 m a⁻¹ derived from the results of Dussaillant *et al.* (2025) for Central Europe (2015-2024). With regard to individual mountain groups, marked differences can be observed: The Stubai Alps exhibit the strongest surface lowering (-11.4 ± 0.15 m; -1.63 ± 0.06 m a⁻¹), primarily due to the influence of the Übeltalferner with its extensive, low-lying, and largely debris-free glacier areas. In contrast, the Texel Group shows the smallest mean surface change (-4.9 ± 0.15 m; -0.70 ± 0.06 m a⁻¹), reflecting the predominance of small glaciers, many of which are debris-covered or situated in favorable micro-topographic settings. In general, small glaciers experience smaller surface-elevation losses, as their persistence often depends on special micro-topographical conditions such as enhanced accumulation due to snow redistribution by wind or avalanches, or a thick debris cover that mitigates melt.

With respect to elevation, the greatest thinning occurred between 2600 m and 2700 m a.s.l., while lower elevations exhibit smaller changes (fig. 2), largely due to the higher proportion of areas covered by a protective debris layer. Significant surface lowering is, however, also evident

Table 3 - Glacier area change by size class. Changes refer to all glaciers assigned to the respective size class at the beginning of the observation period. S_{ref} is to the total area of (the same) glacier parts at the beginning and end of each respective period, ΔS_{ref} to the absolute area change, and $\Delta S_{\text{ref rel}}$ to the relative area change.

Size Class	1997-2023				2017-2023			
	$S_{\text{ref 1997}}$	$S_{\text{ref 2023}}$	ΔS_{ref}	$\Delta S_{\text{ref rel}}$	$S_{\text{ref 2017}}$	$S_{\text{ref 2023}}$	ΔS_{ref}	$\Delta S_{\text{ref rel}}$
[km ²]	[km ²]	[km ²]	[km ²]	[%]	[km ²]	[km ²]	[km ²]	[%]
<0.1 km ²	6.0	1.5	-4.6	-76%	6.7	4.3	-2.4	-35%
0.1-0.5 km ²	23.5	10.7	-12.8	-54%	18.7	15.0	-3.8	-20%
0.5-1 km ²	21.7	11.3	-10.4	-48%	13.2	10.9	-2.3	-17%
1-5 km ²	57.1	38.2	-18.9	-33%	41.7	36.6	-5.0	-12%
>5 km ²	13.8	10.4	-3.4	-25%	5.7	5.3	-0.4	-7%
Overall	122.2	72.1	-50.0	-41%	85.9	72.1	-13.8	-16%

Table 4 - Number of glacier parts and total glacier area per size class in the four homogenized glacier inventories for South Tyrol.

<i>Number of glacier parts</i>						
Inventory	<0.1 km ²	0.1-0.5 km ²	0.5-1.0 km ²	1.0-5 km ²	>5 km ²	Total
1997	172	94	30	27	2	325
2005	250	90	23	25	2	390
2017	451	80	19	20	1	571
2023	625	72	14	17	1	729
<i>Total area of glacier parts [km²]</i>						
Inventory	<0.1 km ²	0.1-0.5 km ²	0.5-1.0 km ²	1.0-5 km ²	>5 km ²	Total
1997	6.0	23.5	21.7	57.1	13.8	122.2
2005	5.8	21.1	15.7	48.9	12.6	104.1
2017	6.7	18.7	13.2	41.7	5.7	85.9
2023	7.3	16.2	10.0	33.4	5.3	72.1

in the highest glacier areas. Even at the Oberer Ortlerferner / Alto del Ortles, the highest glacier in the study area, the mean ice-thickness change since 2016 amounts to -5.1 ± 0.12 m (-0.73 ± 0.05 m a⁻¹).

The total ice-volume loss since 2017 amounts to 0.75 ± 0.03 km³ for the entire study area. Assuming an average ice density of 850 ± 60 kg m⁻³ (Huss, 2013), this corresponds to a mass loss of 635 ± 61 million tons. Relative to the 1997 inventory, glacierized areas have thinned by an average of 20.4 ± 0.2 m, equivalent to a total volume loss of 2.5 ± 0.1 km³ and a corresponding mass loss of approximately 2.1 ± 0.2 Gt.

Uncertainties

This study aimed to compile the South Tyrol Glacier Inventory 2023 as part of a homogenized dataset. To ensure comparability across inventories, certain compromises were necessary when it comes to perfecting individual inventories. While these have minimal impact at the mountain-group or regional scale, they should be considered when analyzing individual glaciers or glacier parts, which was not the primary focus of this work. Al-

though uncertainties in glacier area are difficult to quantify, the main sources of error relate to the delineation of debris-covered glaciers. Based on the 2017 inventory revision, which revealed an area previously underestimated by 2.3%, it can be assumed that the uncertainty of the 2023 area is of similar magnitude, consistent with the relative area uncertainty of 1.9% reported by Reinthaler and Paul (2025).

Uncertainties in calculated elevation changes are primarily determined by the 2023 DTM bias, ranging from -0.06 m in the western Ötztal Alps to -0.21 m in the Zillertal Alps, with a mean of -0.14 m across the study area. The uncertainty in volume changes results from the combination of DTM bias and area uncertainty, ranging from 3.0% in the Ötztal Alps to 5.3% in the Texel Group and Zillertal Alps. For mass change, the uncertainty (averaging 9.7%) is largely governed by the broad density range proposed by Huss (2013).

The mean square deviation of the DTMs over stable areas ranges from 0.2 to 0.3 m (or less) for the periods 2005-2017 and 2017-2023, and approximately 1.5 m for the lower-quality 1999 DTM on which the 1997 inventory is based. While these pixel-level uncertainties are negligible

at the mountain-group scale, results based on the 1999 DTM for individual glaciers should be interpreted with caution.

CONCLUSIONS

The presented glacier inventory 2023 is now the fourth in a series of homogenized glacier inventories for the region of South Tyrol which also comprises the homogenized inventories of 1997, 2005, and 2017. The new inventory includes 729 glacier parts in seven mountain groups with a total area of 72.1 km². Since 2017, the study area has lost 13.8 km², or 16.1% of its glacierized area. Area losses are observed throughout the region, with glaciers east of the Eisack River showing stronger declines than those in the west, largely due to topographical factors such as the prevalence of large but relatively thin glaciers in the east. The Texel Group in the west is an exception, hosting small, highly responsive glaciers.

Ongoing glacier thinning has led to increased fragmentation. While the 1997 and 2017 inventories listed 325 and 571 glacier parts, respectively, the number increased to 729 in the 2023 inventory. Of these, 625 glaciers (86%) are smaller than 0.1 km², accounting for about 10% (7.3 km²) of the total glacierized area. Analyses also indicate a marked increase in debris-covered areas, although their quantitative assessment was beyond the scope of this study.

The mean surface elevation change since 2017 is -8.7 ± 0.14 m, corresponding to an annual rate of -1.27 ± 0.06 m a⁻¹. The resulting volume loss for the study area is 0.75 ± 0.03 km³, equivalent to a mass loss of 635 ± 61 million tons. Significant decrease in surface elevation of several meters was recorded even in the highest-elevation zones of the study area. The most pronounced thinning, however, occurred on larger glaciers with little or no debris cover, whereas low-lying glacier parts benefiting from shading or enhanced snow accumulation due to redistribution of snow by wind or avalanches exhibited smaller changes. Above-average loss was observed for the mass-balance glaciers Hangender Ferner (-12.7 m, Stubai Alps), Übeltalferner (-11.9 m, Stubai Alps), Langenferner (-11.6 m, Ortler Alps), with Westlicher Rieserferner (-6.8 m, Rieserferner Group) as a notable exception.

Consistent with recent projections of glacier evolution in the European Alps (Zekollari *et al.*, 2024; Hartl *et al.*, 2025), the observations of this study, including the widespread absence of accumulation areas and the substantial decline in surface elevation even at the highest glacier areas, indicate that most glaciers of the study region may largely disappear within the coming decades, except for small remnants around the highest peaks of the study area and in topographically favorable locations.

ACKNOWLEDGMENTS

This study was initiated and funded by the Civil Protection Agency of the Autonomous Province of Bolzano-South Tyrol through the Office for Hydrology and Dams (formerly the Hydrographic Office). We gratefully acknowledge the constructive and efficient support of Erik Bollman and Vermessung AVT-GmbH in data processing and interpretation. The manuscript benefited substantially from the thoughtful and constructive comments of two anonymous reviewers and our colleague Christian T. Wild.

REFERENCES

- Abermann J., Lambrecht A., Fischer A., Kuhn M., 2009. *Quantifying changes and trends in glacier area and volume in the Austrian Ötztal Alps (1969-1997-2006)*. The Cryosphere, 3, 205-215. <https://doi.org/10.5194/tc-3-205-2009>
- Abermann J., Kuhn M., Fischer A., 2011. *Climatic controls of glacier distribution and glacier changes in Austria*. Annals of Glaciology, 52 (59), 83-90. <https://doi.org/10.3189/172756411799096222>
- Baroni C., Bondesan A., Carturan L., Chiarle M., Scotti R. (Eds), 2023. *Annual glaciological survey of Italian glaciers (2022)*. Geografia Fisica e Dinamica Quaternaria, 46 (1-2), 3-123. <https://doi.org/10.4454/gfdq.v46.883>
- Berthier E., Vincent C., Six D., 2024. *Exceptional thinning through the entire altitudinal range of Mont-Blanc glaciers during the 2021/22 mass balance year*. Journal of Glaciology, 70, e30. <https://doi.org/10.1017/jog.2023.100>
- Carturan L., Cazorzi F., De Blasi F., Dalla Fontana G., 2015. *Air temperature variability over three glaciers in the Ortles-Cevedale (Italian Alps): effects of glacier fragmentation, comparison of calculation methods, and impacts on mass balance modeling*. The Cryosphere, 9, 1129-1146. <https://doi.org/10.5194/tc-9-1129-2015>
- Dussailant I., Hugonnet R., Huss M., Berthier E., Bannwart J., Paul F., Zemp M., 2025. *Annual mass change of the world's glaciers from 1976 to 2024 by temporal downscaling of satellite data with in situ observations*. Earth System Science Data, 17, 1977-2006. <https://doi.org/10.5194/essd-17-1977-2025>
- Galos S.P., Klug C., Prinz R., Rieg L., Dinale R., Sailer R., Kaser G., 2015. *Recent glacier changes and related contribution potential to river discharge in the Vinschau/Val Venosta, Italian Alps*. Geografia Fisica e Dinamica Quaternaria, 38 (2), 143-154. <https://doi.org/10.4461/GFDQ.2015.38.13>
- Galos S.P., Klug C., Dinale R., 2022. *20 years of glacier change: the homogenized glacier inventories for South Tyrol 1997-2005-2017*. Geografia Fisica e Dinamica Quaternaria, 45 (2), 171-183. <https://doi.org/10.4461/GFDQ.2022.45.6>
- Galos S.P., Klug C., Dinale R., 2023. *The homogenized glacier inventories for South Tyrol 1997-2005-2017 (Version 1) [Dataset]*. Zenodo. <https://doi.org/10.5281/zenodo.7615565>
- Galos S.P., Klug C., Dinale R., 2025. *The homogenized glacier inventories for South Tyrol 1997-2005-2017-2023 (Version 2025) [Dataset]*. Zenodo. <https://doi.org/10.5281/zenodo.16983033>
- GLAMOS, Bauder A., Huss M., Linsbauer A. (Eds), 2024. *The Swiss Glaciers 2021/22 and 2022/23*. Glaciological Report No. 143/144 of the Swiss Commission for Cryosphere observation of the Swiss Academy of Sciences (SCNAT), 155 pp. https://doi.org/10.18752/glrep_143-144
- Hartl L., Schmitt P., Schuster L., Helfricht K., Abermann J., Maussion F., 2025. *Recent observations and glacier modeling point towards*

- near-complete glacier loss in western Austria (Ötztal and Stubai mountain range) if 1.5 °C is not met. *The Cryosphere*, 19, 1431-1452. <https://doi.org/10.5194/tc-19-1431-2025>
- Hugonnet R., McNabb R., Berthier E., Menounos B., Nuth C., Girod L., Farinotti D., Huss M., Dussaillant I., Brun F., Kääb A. 2021. *Accelerated global glacier mass loss in the early twenty-first century*. *Nature* 592, 726-731. <https://doi.org/10.1038/s41586-021-03436-z>
- Huss M., 2013. *Density assumptions for converting geodetic glacier volume change to mass change*. *The Cryosphere*, 7, 877-887. <https://doi.org/10.5194/tc-7-877-2013>
- Marzeion B., Hock R., Anderson B., Bliss A., Champollion N., Fujita K., Huss M., Immerzeel W.W., Kraaijenbrink P., Malles J.H., Maussion F., Radić V., Rounce D.R., Sakai A., Shannon S., van de Wal R., Zekollari H., 2020. *Partitioning the uncertainty of ensemble projections of global glacier mass change*. *Earth's Future* 8, e2019EF001470. <https://doi.org/10.1029/2019EF001470>
- Paul F., Rastner P., Azzoni R.S., Diolaiut G., Fugazza D., Le Bris R., Nemec J., Rabatel A., Ramusovi M., Schwaizer G., Smiraglia C., 2020. *Glacier shrinkage in the Alps continues unabated as revealed by a new glacier inventory from Sentinel-2*, *Earth System Science Data*, 12, 1805-1821. <https://doi.org/10.5194/essd-12-1805-2020>
- Pfeffer W.T., Arendt A.A., Bliss A., Bolch T., Cogley J.G., Gardner A.S., Hagen J.-O., Hock R., Kaser G., Kienholz C., Miles E.S., Moholdt G., Mölg N., Paul F., Radić V., Rastner P., Raup B.H., Rich J., Sharp M.J., The Randolph Consortium, 2014. *The Randolph Glacier Inventory: a globally complete inventory of glaciers*. *Journal of Glaciology*, 60 (221), 537-552. <https://doi.org/10.3189/2014JG13J176>
- Reinthal J., Paul F., 2025. *Reconstructed glacier area and volume changes in the European Alps since the Little Ice Age*. *The Cryosphere*, 19, 753-767. <https://doi.org/10.5194/tc-19-753-2025>
- Schuster L., Maussion F., Rounce D.R., Ultee L., Schmitt P., Lacroix F., Frölicher T.L., Schleussner CF., 2025. *Irreversible glacier change and trough water for centuries after overshooting 1.5 °C*. *Nature Climate Change*, 15, 634-641. <https://doi.org/10.1038/s41558-025-02318-w>
- Strasser U., Marke T., Braun L., Escher-Vetter H., Juen I., Kuhn M., Maussion F., Mayer C., Nicholson L., Niedertscheider K., Sailer R., Stötter J., Weber M., Kaser G., 2018. *The Rofental: a high Alpine research basin (1890-3770 m a.s.l.) in the Ötztal Alps (Austria) with over 150 years of hydrometeorological and glaciological observations*. *Earth System Science Data*, 10, 151-171. <https://doi.org/10.5194/essd-10-151-2018>
- Voordendag A., Prinz R., Schuster L., Kaser G., 2023. *Brief communication: The Glacier Loss Day as an indicator of a record-breaking negative glacier mass balance in 2022*, *The Cryosphere*, 17, 3661-3665. <https://doi.org/10.5194/tc-17-3661-2023>
- WGMS (World Glacier Monitoring Service), 2025. *Fluctuations of Glaciers (FoG) Database*. Zurich, Switzerland. <https://doi.org/10.5904/wgms-fog-2025-02b>
- Wimberly F., Ultee L., Schuster L., Huss M., Rounce D.R., Maussion F., Coats S., Mackay J., Holmgren E., 2025. *Inter-model differences in 21st century glacier runoff for the world's major river basins*, *The Cryosphere*, 19, 1491-1511. <https://doi.org/10.5194/tc-19-1491-2025>
- Zekollari H., Huss M., Schuster L., Maussion F., Rounce D.R., Aguayo R., Champollion N., Compagno L., Hugonnet R., Marzeion B., Mojtavavi S., Farinotti D., 2024. *Twenty-first century global glacier evolution under CMIP6 scenarios and the role of glacier-specific observations*, *The Cryosphere*, 18, 5045-5066. <https://doi.org/10.5194/tc-18-5045-2024>

(Ms. received 5 September 2025, accepted 3 November 2025)